THE APPLICATION OF THE HYDROCYCLONE TO THE SEPARATION OF GLUTEN AND STARCH IN AQUEOUS SUSPENSION

by

STEWART H. MILLSTONE

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TABLE OF CONTENTS

INTRODUCTION

Starch, as it is found in cereal grains, is enmeshed with a complex network of gluten, a protein substance, which must be removed both because its presence is unsuitable for most uses of the product, and because it greatly inhibits filtration. Starch production necessarily involves a number of unit processes and operations, several of which are concerned solely with the separation of starch and gluten.

Generally, in a production plant, the grains will be de-branned, ground in a water slurry, and screened to give an aqueous suspension of starch and gluten of relatively uniform particle size. The milling operation and subsequent transport of the material requires a low concentration of solids in the carrier liquid. Therefore, succeeding operations are concerned with increasing solids concentration, and separation of the gluten and starch.

Since the starch is, by nature, a more dense material than the gluten, gravitational settling trays, called tables, have served to separate the two components. However, such equipment is cumbersome, occupies a great deal of floor space, and usually requires a subsequent thickening operation before filtration of the product. More recently centrifuges have been used with considerable improvement in efficiency and large savings in floor space. The purpose of this work was to investigate the possibility of separating gluten and starch, through the use of a hydrocyclone, a relatively simple device with no moving parts and which occupies very little space.

The hydrocyclone, also known as the hydroclone or liquid cyclone, is a device whose usual function is the separation of finely divided solid particles from liquid suspensions where the particles themselves are too finely divided to settle under gravitational forces alone at a rate consistent with economic

considerations. Its main advantages over other types of separation devices are the simplicity of the device in that it employs no moving parts, and the sharpness of classification of particles which it achieves. Unlike most equipment of this nature, the design of the hydrocyclone is not based on the desired capacity, but rather on the desired size of separation since the sharpness of classification decreases with increasing cyclone diameter. Maximum efficiency usually requires a bank of small hydrocyclones as opposed to a single large unit.

The hydrocyclone presently finds most use in the mining industries, particularly in coal mining, where water slurries containing extremely fine particles must be refined. The cyclone also has applications in liquid-liquid separation, separation of several solids of different specific gravity in liquid slurries, and general concentration of solids dispersed in liquid mediums. The Dorr company, as well as some others, is presently manufacturing these units in sizes ranging from two inch to three foot diameters.

Physically, the hydrocyclone is a conical section with a cylindrical extension at its base (see Plate II). The feed enters tangentially in the cylindrical section at a slightly declined angle to create a vortex motion. The slight angle of declination of the feed conduit is necessary to give the feed a small downward component of velocity so that at the completion of one revolution, the fluid and solids do not interfere with the entering feed. "Sink" solids are thrown to the outer radii by the centrifugal force and are conducted by spiral flow currents to the apex of the conical section, where they are discharged as an underflow product. The bulk of the fluid with float and extremely fine sink solids migrates to the vortex finder where it is discharged as an overflow product. The vortex finder is a tube which

extends into the cylindrical section of the hydrocyclone just below the feed port but at a small distance from the entrance to the conical section.

In the design and operation of the hydrocyclone, there are a large number of controllable variables such as the included angle of the cyclone, length of the cylindrical section, cyclone diameter, size of the feed and discharge openings, feed pressure, length of the vortex finder, back pressure at the discharge ports, etc. Most of these factors, such as the cyclone included angle, are determined more or less from practical experience. As a rule of thumb, the usual practice has been to use a ten degree included angle for cyclone diameters of about two inches or less, a twenty degree included angle for diameters between two and approximately twenty inches, and a thirty degree included angle for cyclones larger than twenty inches in diameter. Included angles greater than thirty degrees are uncommon.

The diameter of the hydrocyclone is primarily related to the size of separation. As an example, three inch cyclones will classify in the neighborhood of five to twenty microns, while twenty-four inch cyclones will classify in the one hundred to one hundred-fifty micron range (7). Obviously, in the five to twenty micron range it will usually be necessary to use several small units operated from a common manifold to provide the required capacity.

Once the cyclone has been selected, the main control over the size of separation is in the diameter of the feed entrance and the vortex finder tube. In general, the smaller the openings, the finer size of separation will be obtained, but if the orifices are too small, the separation again becomes coarser. For a minimum size of separation, the feed entrance and vortex finder tube usually have equivalent diameters in the range of one-fifth to one-sixth of the diameter of the cyclone, but this may vary with the nature of the feed (7).

It is desirable to have replaceable feed conduits and vortex finder tubes, particularly in the case of new applications.

The apex discharge orifice is probably the most critical of the operating variables, especially if maximum efficiency of separation is required or if large fluctuations occur in the feed. If this opening is too large, the underflow will contain a considerable amount of liquid. Since this liquid will contain proportionately as much of the finest particles as the overflow liquid, the underflow product may be contaminated with an undesirable amount of fine particles. To avoid this, the underflow discharge orifice should be as small as possible. However, if too small, it may prevent discharge of the coarse solids as fast as they reach the apex, with the result that some of the coarse particles will be forced out the overflow. The appearance of the underflow discharge shows whether this condition exists. In normal operation, the discharge is in the form of an inverted funnel-shaped spray, but if the opening is too small, the underflow is extruded in a thick ribbon somewhat resembling a rope in appearance (7).

In principle, the hydrocyclone operates as a free-vortex (potential vortex) resembling the natural phenomena of whirlpools and atmospheric cyclones. Principally, two spiral flow patterns exist with the cyclone (see Plate I). The outer spiral travels toward the apex of the cyclone while the inner spiral rotates in the same manner towards the vortex finder. The outer radius of the inner spiral and the inner radius of the outer spiral appear to increase until they are slightly larger than the vortex finder radius at the plane of entrance to the overflow discharge. Because the direction of the inner spiral is toward the vortex finder, an air core exists in the cyclone if both exit ports are at atmospheric pressure. Correct application of back pressure to

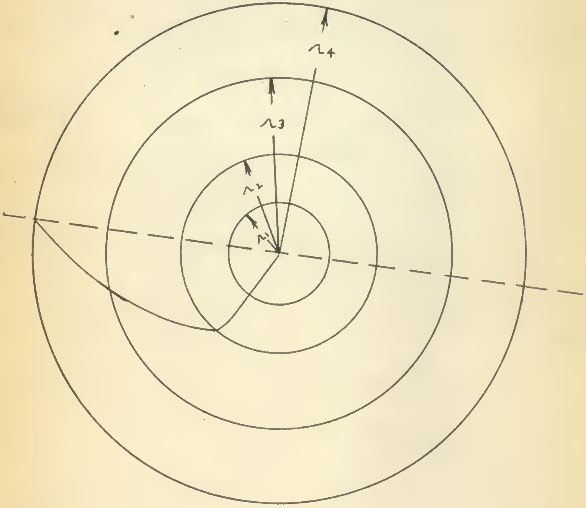
EXPLANATION OF PLATE I

Radial Velocity Profile of the Combined Vortex

Radial velocity increases with increasing radius from r_0 to r_2, corresponding to the radius of the vortex finder in the hydrocyclone. At a distance from the center greater than r_2, radial velocity decreases with increasing radius, and will assympototically approach zero at the wall of the cyclone.

(Diagram from Rause, H., Fluid Mechanics for Hydraulic Engineers, New York; McGraw Hill, 1938, p. 76)

PLATE I



the underflow, however, will eliminate the air core without loss of efficiency (2).

The pressure at which the feed is supplied to the cyclone affects the operation in several ways. Increased pressure permits increased throughput, hence, higher capacity. The increased velocity causes high centrifugal force within the cyclone, which tends to decrease the size of separation. However, this effect is partly offset by the shorter residence time in the cyclone. The disadvantage of higher pressures other than increased pumping costs is that it causes greater wear. Pressures normally employed range from ten to one-hundred pounds per square inch (7).

The centrifugal force generated is not a major function of the cyclone diameter. However, because of the required ratios that must be maintained between feed and overflow diameters and the cyclone diameter for maximum efficient transformation of feed pressures into rotational kinetic energy, smaller diameter cyclones produce higher centrifugal forces.

The most important velocity and its distribution in a free vortex is the tangential component as it supplies the centrifugal force factor $V^2 tr$. By the principle of conservation of momentum, an ideal nonviscous fluid would exhibit a tangential velocity distribution as indicated by the following equation:

$$V_t = K'/r$$

For gas cyclones, this equation was found to be followed with the value of r raised to the exponent n where n ranged from 0.5 to 0.7, the former value being generally accepted.

$$V_t = K''/r^n$$

In the investigation of a three inch cyclone, Dahlstrom (2) found that this same equation was followed with the exponent n ranging from 0.77 to 0.84 using water as a liquid medium. Undoubtedly the higher exponent with water is due in great part to the lower kinematic viscosity as compared to that of air.

This equation would predict an infinite tangential velocity at the center line. Actually, it has been found for both gas and liquids that the inner spiral tends to act as a forced vortex exhibiting relatively constant angular velocity. Thus, a low tangential velocity exists at the center line. Observation in a two inch glass cyclone showed that when the underflow was blocked off, a thin thread of air still persisted at the center line for an extended period of time (2).

Except for regions near the cyclone wall and the vortex finder outer wall, the relationship between V_t and r was found to be independent of the vertical elevation in the cyclone. Furthermore, although the tangential velocity will increase with feed rate, the location of maximum tangential velocity remains constant. For this same three inch cyclone, it was found that:

$$V_{tr} = \Phi(\Delta P)^{0.52}$$

$$V_{tr} = \Phi(GPM_t)^{1.115}$$

where V_{tr} is the tangential velocity at any radius and ΔP is the cyclone pressure drop (2).

Another relationship, developed through a consideration of the pressure drop through a sharp orifice (Bernoulli's equation), can be used to relate feed pressure to cyclone throughput, assuming the other factors involving

cyclone operation have been properly designed. This relationship is:

$$q = 12(A)\ (\Delta P)^{1/2}$$

where q is the total throughput expressed in gallons per minute, (A) is the area of the feed inlet in inches, and ΔP is the cyclone pressure drop in pounds per square inch (1).

In the preceding, various relationships involving the major design factors in the operation of the hydrocyclone have been expressed. There are many other relationships developed by experimenters working with liquid cyclones, which have not been included here. It will be noted that most of the equations are empirical in nature, and much work remains to be done in this particular field. In determining the factors affecting the separation of gluten and starch, an empirical approach yielding relationships similar to those given in the above was adopted. The results so obtained were found to be satisfactory only in a very definite range of variables in as much as certain "threshold effects" prevent extrapolation of the empirical relationships.

EQUIPMENT AND OPERATION

The hydrocyclone used in this work was three and one-half inches in internal diameter with a cylindrical section found and one-quarter inches in length and a conical section with a twenty degree included angle eight and nine thirty-seconds inches in length. The conical section was fabricated from a solid brass cylinder four inches in diameter, which was machined internally to form the cone, the apex of which was extended into a threaded cylinder designed to accomodate a one-half inch outside diameter machine threaded

conduit through which the underflow product was withdrawn. A number of these underflow conduits were fabricated with inside dimensions ranging from one-sixteenth to one-quarter inches in diameter, with the upper portion of the conduit reamed out to match the angle of the cone in an attempt to maintain a smooth flow of the underflow product in passing through the transition between the cone and conduit.

The cylindrical section of the hydrocyclone was fabricated from a four inch outside diameter brass tube with a one-quarter inch wall. The feed was introduced through a brass conduit soldered in place one-half inch from the top of the cylinder, the dimension taken between the inner wall of the feed conduit and the top of the cylindrical section. The inner wall of the feed conduit was made tangential to the inner wall of the cylindrical section of the hydrocyclone to produce the vortex motion of the fluid, and a slight downward component of velocity was provided for by inclining the feed conduit three degree with the horizontal. Two such feed conduits were provided in the cylindrical section with an inside diameter of one-quarter and one-half inch respectively, and provision was made for blocking one of these conduits at its point of entry to the cylindrical section while the other was in use, to prevent any interference with normal flow conditions.

A three-eighths inch round brass plate, four inches in diameter, drilled and tapped at its center to accomodate the vortex finder tube, formed the cover to the cylindrical section of the hydrocyclone. Vortex finders ranging in size from one-quarter inch to one-half inch inside diameters were used, and a number of covers were fabricated to accomodate the various sizes of vortex finders. The wall thickness of each vortex finder was made as small as possible so as to minimize interference to the motion of the fluid in the

cyclone. The vortex finder extended a distance of one and one-half inches to two inches above the junction between the cylindrical and conical sections of the hydrocyclone, the former corresponding to the use of the one-half inch feed conduit, and the latter to the one-quarter inch feed conduit. (See Plate II)

The feed material for the hydrocyclone was provided from a pilot starch plant utilizing milo sorghum grain grits. The plant used a hydraulic milling operation and its final product after refinement through a two-hundred mesh screen consisted of a liquid suspension of two per cent solids with particle sizes in the range of approximately fifty to seventy microns, the larger particles corresponding to the starch fraction and the smaller particles to the gluten fraction with an overlapping in the mid-range.

The starch plant product was collected in a stainless steel storage tank equipped with a "Lightnin' Mixer" to prevent the heavier particles from settling out during storage. Quantities of sixty gallons of starch plant product were produced per experimental run, and each run was carried out in the space of three hours or less to prevent fermentation of the product.

The hydrocyclone was operated through a range of feed pressures from ten to forty pounds per square inch gauge. Pressure was provided from a centrifugal pump with a maximum pressure head of fifty pounds per square inch gauge. Back pressure at the overflow conduit was provided by two methods; a horseshoe shaped galvanized pipe column, ninety-two inches in overall height, provided with gate valves permitting the flowing fluid to rise to levels of seventeen, forty-two, sixty-seven, and ninety-two inches was connected to the overflow conduit. The column was fabricated of pipe

EXPLANATION OF PLATE II

Hydrocyclone

A. Vortex Finder Conduit

B. Feed Inlet Conduit

C. Underflow Conduit

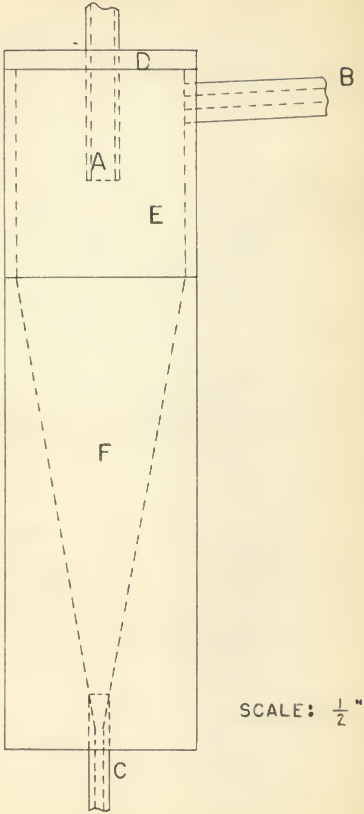
D. Hydrocyclone Cover Plate

E. Cylindrical Section of Hydrocyclone

F. Concial Section of Hydrocyclone

(For dimensions see discussion under "Equipment and Operation".)

PLATE II



SCALE: $\frac{1}{2}$" = 1"

sufficiently large to render negligible pressure losses due to frictional effects of the flowing fluid. A vent was provided at the top of the column to prevent syphon effects, and the fluid was collected in a measuring device upon exit from the column.

The second method was simply the insertion of a gate valve in the overflow exit line of the hydrocyclone. In this case, pressures were measured either with the use of a mercury manometer or a pressure gauge calibrated directly in pounds per square inch, depending upon the relative magnitude of the back pressures employed. The galvanized pipe column was used mainly in conjunction with the one-quarter inch feed conduit in which case back pressures of greater magnitude than ninety-two inches were not required. The gate valve arrangement was used in conjunction with the one-half inch feed conduit where back pressures of as much as twenty pounds per square inch gauge were required.

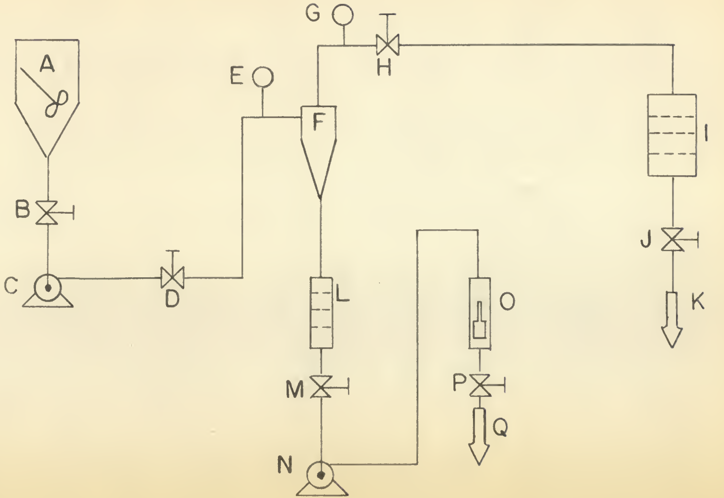
Volumetric flow rates through the overflow conduit were measured with the use of a glass pipe twelve inches in diameter provided with a quick opening valve at its base. The fluid passing through the overflow conduit was discharged into this glass pipe and the time required to collect twelve liters of fluid was measured. Similarly, the underflow conduit discharged at atmospheric pressure into a two inch glass pipe, and the time required to collect five-hundred cubic centimeters of fluid was measured. The total volumetric throughput was measured indirectly as the sum of the overflow and underflow streams. Specific gravities of the various streams were determined with the use of a hydrometer float, and subsequently reported as weight percent solids by suitable conversion charts constructed expressly for this purpose. Samples of the various streams were filtered, dried, and

EXPLANATION OF PLATE III

Schematic Diagram of Experimental Apparatus

A. Storage Tank for Pilot Starch Plant Product
B. Storage Tank Shut-Off Valve
C. Hydrocyclone Feed Pump (Centrifugal)
D. Hydrocyclone Feed Pressure Regulating Valve
E. Hydrocyclone Feed Pressure Gauge
F. Hydrocyclone
G. Hydrocyclone Overflow Pressure Gauge
H. Hydrocyclone Overflow Back Pressure Control Valve
I. Glass Collection Vessel for Measurement of Overflow Volumetric Flow Rates
J. Overflow Measurement Vessel Outlet Valve
K. Recycle or Waste Line
L. Glass Collecting Vessel for Measurement of Underflow Volumetric Flow Rates
M. Underflow Collection Vessel Outlet Valve
N. Centrifugal Pump
O. Glass Vessel with Hydrometer Float for Measurement of Underflow Specific Gravity
P. Specific Gravity Vessel Outlet Valve
Q. Recycle or Waste Line

PLATE III

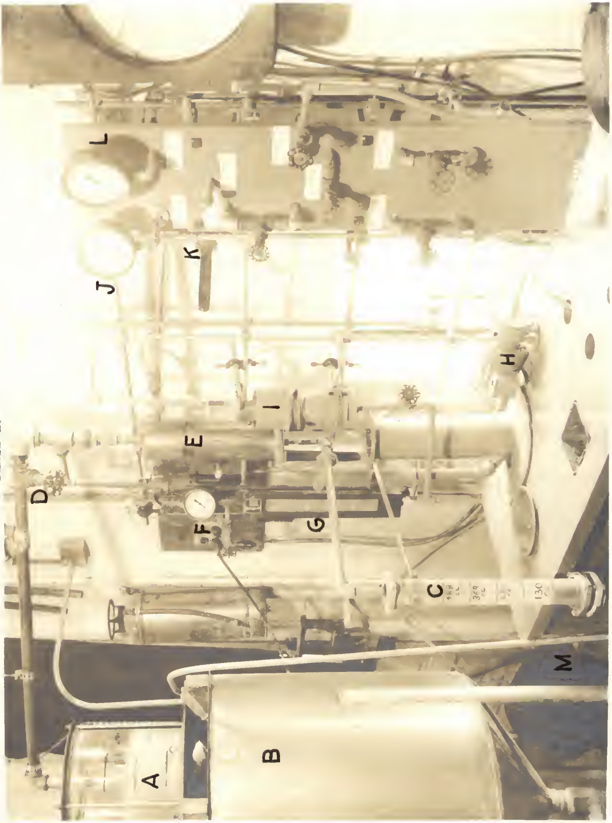


EXPLANATION OF PLATE IV

Photograph of Experimental Apparatus

A. Glass Vessel for Measurement of Overflow Volumetric Flow Rate
B. Storage Tank for Pilot Starch Plant Product
C. Glass Vessel for Measurement of Underflow Volumetric Flow Rate
D. Overflow Back Pressure Control Valve
E. Hydrocyclone
F. Overflow Back Pressure Gauge
G. Overflow Back Pressure Mercury Manometer
H. Centrifugal Feed Pump to Specific Gravity Measuring Apparatus
I. Specific Gravity Measuring Apparatus
J. Hydrocyclone Feed Pressure Gauge
K. Hydrocyclone Feed Pressure Control Valve
L. Hydrocyclone Pump Pressure Gauge
O. Hydrocyclone Centrifugal Feed Pump

PLATE IV



analyzed for total nitrogen content by the Kjeldahl method to determine the relative concentration of gluten in each stream.

DATA AND RESULTS

In the determination of the variables controlling the operation of the hydrocyclone, one of the most critical factors in the separation of gluten and starch was found to be the volume split between the overflow and underflow conduits. The final starch product is usually considered satisfactory if the gluten content is less than 0.5 per cent, and thus the experiment was designed so as to produce a product meeting these specifications as closely as possible. The original data are reported in Tables 1 through 6 in the appendix.

Although the gluten content was reduced considerably through the use of the hydrocyclone, the maximum separation which we were able to obtain was slightly above one-half per cent, with the lowest values in the range 0.6 to 0.7 per cent gluten, the feed material being approximately six per cent gluten. These values were obtained at exceedingly low underflow rates, usually below one per cent of the total flow through the cyclone which, in the case of the one-half inch feed conduit, ranged between 10 and 15 gallons per minute. Although the total volume of material discharged at the underflow exit was small, nevertheless, with the use of the one-half inch feed conduit, the concentration of solids at these low flow rates was increased as much as twenty-fold, the underflow product being in the vicinity of forty percent solids while the feed solids concentration remained relatively constant at two per cent solids. Graphical representations of the percentage of gluten and weight percentage of solids in the underflow as functions of

the percentage of the total volumetric flow in the underflow are shown in Figs. 1 and 2.

It will be noted that the data are scattered considerably about the curves drawn. Measurement of the volume split in the hydrocyclone was apparently quite accurate as will be demonstrated later, and the maximum error involved in the Kjeldahl analysis of the underflow product was $\pm$ 0.25 per cent gluten, so that the large deviations of the data points about the curve drawn can be only partially explained by the experimental error involved. In the construction of these curves, no consideration was given to the feed pressure to the hydrocyclone, or to the size of the underflow and overflow orifices except in the respect that they determine the volume split. The data so obtained do not warrant reclassification according to these variables, as it was found that no difference was apparent between the product obtained at different feed pressures, underflow orifices, etc., but at the same volume split. However, it is probable that certain of the interactions between these variables have a marked effect on the nature of the underflow product, and result in the scattering of the data when plotted as a function of the volume split only.

The volume split in the hydrocyclone was found to be primarily a function of the feed pressure, size of the underflow orifice, and size of the overflow orifice for the hydrocyclone considered. The volume split will, of course, also depend upon such other variables as the cone angle, size of feed conduit, declination of the feed conduit, etc. A linear relationship was found between the percentage of the total flow in the underflow (%U), and the factor ϕ, defined as:

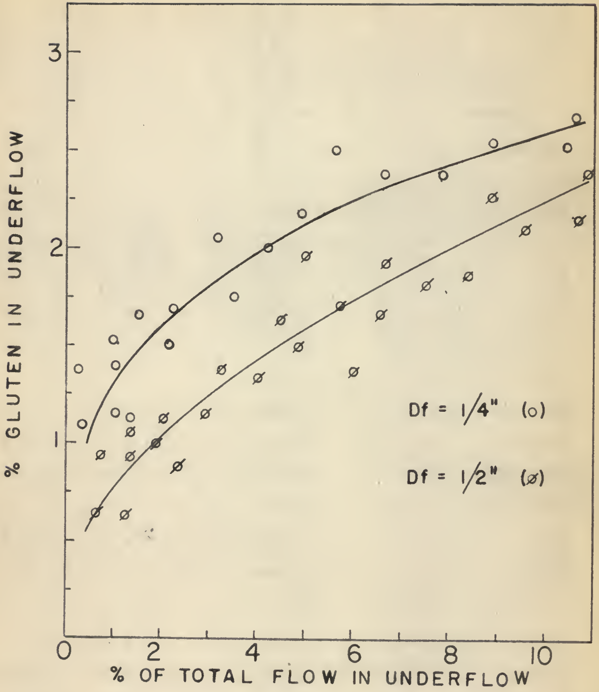


Fig. 1. The effect of volume split in the hydrocyclone on the percentage of gluten in the underflow product.

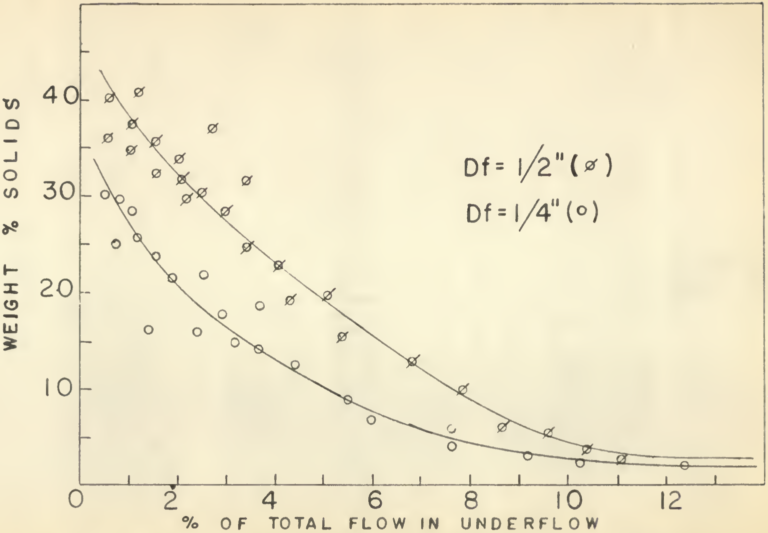


Fig. 2. The effect of volume split in the hydrocyclone on the percentage of solids in the underflow product.

$$\phi = \frac{\log P_o}{D_o(1-D_u)}$$

where P_o is the back pressure at the overflow conduit, expressed in inches of water, D_o and D_u are the diameters of the overflow and underflow conduits respectively, expressed in inches. Statistical analysis of the data obtained yielded an expression of the form:

$$\%U = k\phi + C$$

where k and C depend upon the feed pressure and diameter of the feed conduit. The analysis of covariance can be found in Tables 5 and 7 in the appendix. R^2, the fraction of the total variance explained by the prediction equation, is 0.9 or higher, indicating excellent correlation of the data. Graphical representations of the volume split as a function of the factor ϕ are shown in Figs. 3 and 4.

The total volumetric throughput of the hydrocyclone was found to be a function of the pressure drop between the feed and overflow conduits. Pressure drop was measured as the difference between the pressure in the feed line just outside the entrance to the hydrocyclone, and the back pressure in the overflow conduit, also measured just outside the overflow exit to the hydrocyclone.

$$GPM_t = k'\Delta P^{1/2} + C'$$

where GPM_t is the total volumetric flow through the hydrocyclone, expressed in gallons per minute, ΔP is the feed to overflow pressure drop, expressed in pounds per square inch, and k' and C' are functions of the size of feed

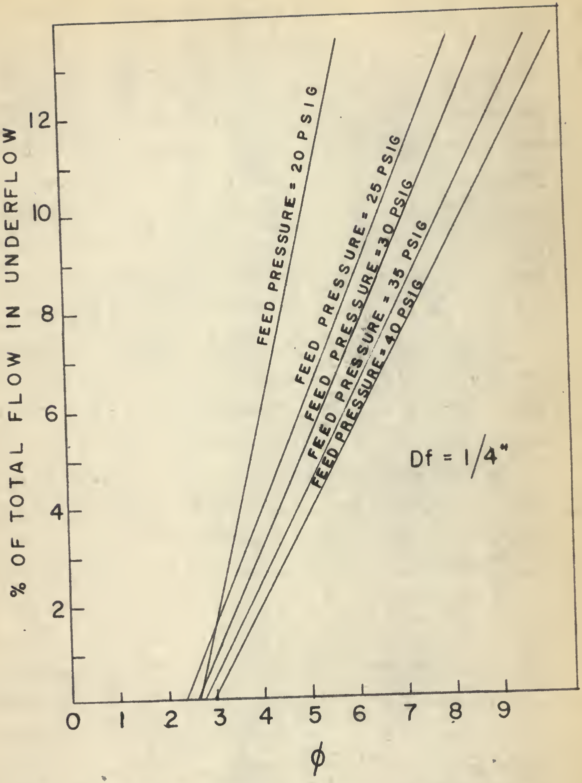


Fig. 3. The effect of the factor ϕ on volume split in the hydrocyclone for a feed diameter of 1/4-inch. $\phi = \log P_o / D_o(1-D_u)$.

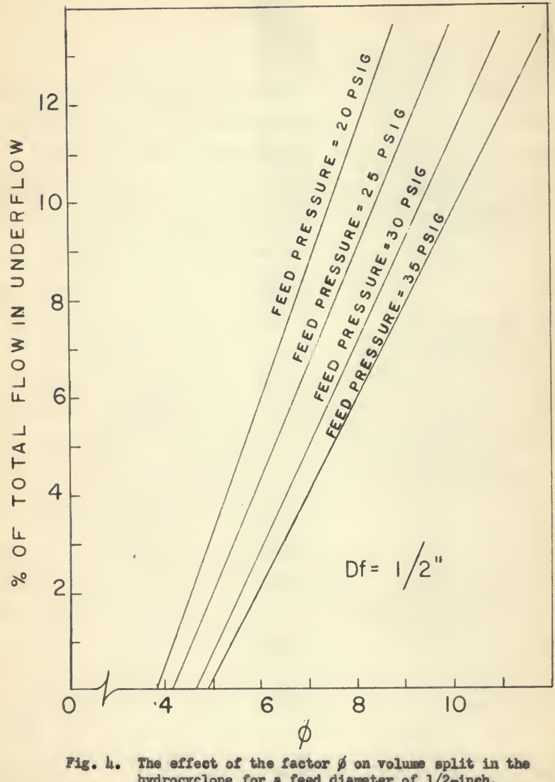


Fig. 4. The effect of the factor ϕ on volume split in the hydrocyclone for a feed diameter of 1/2-inch. $\phi = \log P_o / D_o(1-D_u)$.

and overflow conduits. Linear regression analysis of the data can be found in Table 3 of the appendix. Note that here also, the value of R^2 is 0.9 or larger indicating excellent agreement of the data with the prediction equation. A graphical representation of the prediction equation is given in Fig. 5.

It is necessary to emphasize that the relationships obtained above apply only to the range of variables considered, and are not necessarily extensible, particularly since several "threshold effects" are known to exist.

DISCUSSION AND CONCLUSIONS

In the previous section, it was demonstrated that the separation of gluten and starch can be achieved in the hydrocyclone, reducing the concentration of gluten from six per cent in the feed material to less than 0.7 per cent in the underflow product. It is also evident that the gluten content is reduced with increase in the size of feed conduit, and it is therefore reasonable to assume that the percentage of gluten in the underflow product can be reduced further by increasing the size of feed and overflow conduits.

This apparent increase in the separation with increase in the feed and overflow conduits is mainly a result of the increased centrifugal force obtained with the larger conduits. As mentioned earlier, the centrifugal force obtained is not a major function of the cyclone diameter, but increases with increasing size of feed and overflow conduits until an optimum ratio to the cyclone diameter is reached. At this ratio the conversion of potential energy to kinetic energy in the hydrocyclone is at maximum efficiency.

The lower separation obtained with the 1/4-inch feed conduit as opposed to the 1/2-inch feed conduit probably results from the fact that the 1/4-inch

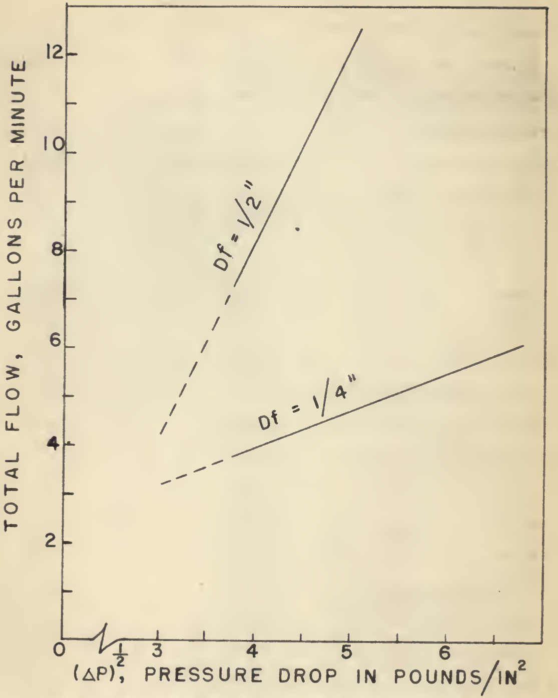


Fig. 5. The effect of the pressure drop through the hydrocyclone on the total volumetric flow.

conduit is not sufficiently large to permit maximum energy transformation. Likewise, there is no evidence that maximum transformation is obtained with the use of 1/2-inch feed conduit, and hence a further increase of the feed and overflow conduits may increase the centrifugal force, resulting in a more efficient separation.

The main objection to the use of the existing hydrocyclone then lies not in its ability to effect the separation of gluten and starch, but in the relatively low recovery of the starch in the underflow product. The specific gravity of the underflow product in the region of satisfactory operation ranges between 1.08 and 1.15 so that under the conditions necessary to reduce the gluten content to a satisfactory level, only 20 per cent of the starch in the feed material can be recovered in a single pass.

Since the percentage of gluten in the underflow appears to be a function of the split between the overflow and underflow rather than an underflow rate under a given set of conditions, the recovery of starch per pass is independent of the total throughput, except in as much as the total flow rate affects the centrifugal force obtained. This leaves several methods by which the recovery can be increased. The fraction of the total flow which can be removed at the underflow must necessarily be low when using a feed material with only two per cent solids, since we can remove only the solids which have been thrown to the wall of the hydrocyclone. If we attempt to remove too large a fraction of the total flow, the underflow product will contain large amounts of liquid which has essentially the same concentration of gluten as the overflow material. Therefore, by increasing the concentration of solids in the feed material, a greater percentage of the total flow probably could be removed at the underflow, thus increasing the capacity of the

hydrocyclone for starch production. With the removal of larger quantities of material from the underflow conduit, we can use underflow conduits of larger diameter thus reducing the necessity of employing large overflow back pressures. The lower overflow back pressures should reduce the tendency to force the cyclone liquid out the underflow conduit, so that larger quantities of material might be removed from this conduit without contamination by this liquid, thereby increasing the recovery of starch.

Increasing the diameter of feed and overflow conduits or increasing the feed pressures employed should increase the centrifugal force. A greater fraction of the feed solids would then be thrown to the cyclone wall for subsequent removal at the underflow conduit, thereby increasing the recovery of starch.

From the standpoint of production, a twenty per cent recovery of the starch in the feed material is not very satisfactory. A better method might be the use of several hydrocyclones operated in series, designing the first one or two units as "concentrators", whose main function is the increase in the concentration of total solids. The underflow product from these "concentrators" could then provide the feed material for the final "separating" hydrocyclone, which, because of the increased feed solids, could maintain a larger recovery of starch.

In essence, a large number of variations in process design utilizing the hydrocyclone are possible, several of which could conceivably effect the separation of starch and gluten efficiently and economically. A great deal of work remains to be done to determine in greater detail the principles involved in the separation of the two components and subsequent recovery of the starch fraction. We have attempted to show here that the separation of

gluten and starch in the hydrocyclone is feasible and merits further investigation.

NOMENCLATURE

a	intercept of the least squares regression line
A	cross-sectional area of the feed conduit, $(\text{inches})^2$
b	slope of the least squares regression line
C, C'	intercept of the prediction equation
d^2	sum of squares of the deviations about the mean of the abscissae not explained by linear regression
d.f.	degrees of freedom
D_f	diameter of the feed conduit, inches
D_o	diameter of the overflow conduit, inches
D_u	diameter of the underflow conduit, inches
GPM_o	gallons per minute through the overflow conduit
GPM_t	total gallons per minute through the hydrocyclone
GPM_u	gallons per minute through the underflow conduit
k, k'	slope of the prediction equation
K', K''	constant relating tangential velocity to radius in a vortex
P_o	back pressure at the overflow conduit, inches of water
q	gallons per minute through the feed conduit
r	radius
R^2	fraction of the total variance explained by the prediction equation
%U	percentage of the total flow in the underflow
V_t	tangential velocity
V_{tr}	tangential velocity at any radius

x^2	sum of squares of the deviations about the mean of the ordinates
xy	sum of the crossproducts of the deviations about the mean of the ordinates and abscissae respectively
y^2	sum of squares of the deviations about the mean of the abscissae
ΔP	feed to overflow pressure drop, pounds per square inch
ϕ	functional group expressed as $\dfrac{\log P_o}{D_o(1-D_u)}$

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APPENDIX

Table 1. Total volumetric flow through the hydrocyclone for various pressure drops and underflow diameters. Overflow diameter, 0.50 inches. Feed diameter, 0.25 inches.

ΔP, lb/in^2	$(\Delta P)^{1/2}$	Flow, gal/min for underflow diameter, D_u, inches		
		1/16	3/32	1/8
40.00	6.325	5.818	5.841	5.828
38.44	6.200	5.741	5.728	5.690
37.51	6.125	5.669	5.656	5.672
36.58	6.048	5.618	5.623	5.641
35.00	5.916	5.492	5.500	5.518
33.44	5.783	5.420	5.418	5.428
32.51	5.702	5.342	5.352	5.332
31.58	5.619	5.189	5.274	5.286
30.00	5.477	5.165	5.152	5.160
28.44	5.333	5.081	5.053	5.062
27.51	5.245	5.002	4.981	4.965
26.58	5.155	4.900	4.891	4.927
25.00	5.000	4.790	4.800	4.787
23.44	4.842	4.646	4.666	4.653
22.51	4.745	4.581	4.580	4.592
21.58	4.646	4.509	4.522	4.518
20.00	4.472	4.374	4.358	4.359
18.44	4.294	4.239	4.250	4.247
17.51	4.185	4.202	4.013	4.150
16.58	4.072	4.058	4.061	4.083

Table 2. Total volumetric flow through the hydrocyclone for various pressure drops and underflow diameters. Overflow diameter, 0.50 inches. Feed diameter, 0.50 inches.

ΔP, lb/in^2	$(\Delta P)^{1/2}$	Flow, gal/min for underflow diameter, D_u, inches	
		1/16	1/8
33.50	5.788	15.720	15.708
32.78	5.725	15.462	15.458
30.00	5.477	14.461	14.432
28.25	5.315	13.782	13.769
26.53	5.151	13.095	13.107
25.00	5.000	12.451	12.512
23.67	4.865	11.900	11.388
20.00	4.472	10.196	10.291
18.36	4.285	9.530	9.530
15.42	3.927	8.067	8.031
15.00	3.871	7.891	7.803
14.13	3.759	7.349	7.399

Table 3. Statistical analysis of tables 1 and 2, total volumetric flow through the hydrocyclone. Least squares regression line. D_f, feed diameter, inches.

D_f	d.f.(b)	x^2	y^2	xy	b	d^2	R^2	a
0.25	58	28.45314	17.65298	22.38707	0.78680	0.03873	0.9978	0.85295
0.50	22	11.60862	196.83766	47.79916	4.11755	0.02188	0.9988	-8.11658

$(x = P^{1/2})$

$(y = GPM_t)$

Table 4. Percent of total flow in underflow, %U, for various values of Ø, underflow diameters and feed pressures. Overflow diameters, 0.50 and 0.3125 inches. Feed diameter, 0.25 inches.

P_f, psig	Ø	% U for underflow diameter, D_u, inches 1/16	3/32	1/8
40	6.678	6.91	7.09	-
40	6.233	6.20	6.15	-
40	4.500	3.07	2.97	-
40	4.489	2.86	3.11	3.12
40	4.334	2.75	2.78	2.70
40	4.200	2.38	2.41	-
40	4.189	2.38	2.28	2.39
40	4.174	2.00	2.35	2.38
40	4.030	2.10	1.96	2.30
40	3.896	1.73	1.78	1.73
40	3.710	1.32	1.43	1.36
40	3.582	1.52	1.51	1.61
40	3.463	0.97	0.85	1.05
35	6.678	7.75	7.80	-
35	6.233	6.78	6.92	-
35	4.500	3.40	3.38	-
35	4.489	2.92	3.58	3.58
35	4.334	3.25	3.28	3.25
35	4.200	2.92	2.85	-
35	4.189	2.80	2.86	2.78
35	4.174	2.68	2.75	2.70
35	4.030	2.59	2.50	2.41
35	3.896	2.10	2.00	2.14
35	3.710	1.63	1.82	1.65
35	3.582	2.01	1.96	2.51
35	3.463	1.55	1.56	1.52
30	6.678	7.75	7.80	-
30	6.233	9.00	8.94	-
30	4.500	3.40	3.35	-
30	4.489	4.38	4.27	5.00
30	4.334	3.96	4.22	4.14
30	4.200	3.52	3.59	-
30	4.189	3.47	3.47	3.58
30	4.174	3.38	3.30	3.38
30	4.030	3.20	3.22	3.33
30	3.896	2.49	2.58	2.61
30	3.710	2.00	2.20	2.12
30	3.582	2.54	2.60	2.51
30	3.463	1.55	1.56	1.52

Table 4. (Concl.)

P_f, psig	ø	% U for underflow diameter, D_u, inches 1/16	3/32	1/8
25	6.678	10.00	10.12	-
25	6.233	9.00	8.92	-
25	4.500	4.42	4.42	-
25	4.489	4.92	5.70	5.68
25	4.334	5.20	5.31	5.32
25	4.200	4.66	4.78	-
25	4.189	4.92	4.64	4.52
25	4.174	4.53	4.42	4.47
25	4.030	4.23	4.33	4.27
25	3.896	3.49	3.52	3.48
25	3.710	2.86	2.75	2.64
25	3.582	3.25	2.97	3.31
25	3.463	2.26	2.18	2.18
20	6.678	16.81	16.88	-
20	6.233	15.00	14.88	-
20	4.500	7.82	7.76	-
20	4.489	6.92	7.86	7.85
20	4.334	7.42	7.42	7.50
20	4.200	6.60	6.51	-
20	4.189	6.40	6.53	6.55
20	4.174	6.27	6.17	6.25
20	4.030	5.96	5.85	6.00
20	3.896	4.82	4.71	5.00
20	3.710	4.10	4.02	4.11
20	3.582	4.75	4.70	4.68
20	3.463	3.17	3.00	3.21

Table 5. Analysis of variance of table 4, volume split in the hydrocyclone for various values of ∅, underflow diameters and feed pressures. Overflow diameters, 0.50 and 0.3125 inches. Feed diameter, D_f, 0.25 inches.

SOURCE	d.f.	x^2	y^2	xy	b	R^2	d^2	d.f.	M.S.	a
40	34	24.47590	84.99986	45.42367	1.856	0.9917	0.70022	33		-5.384
35	34	24.47590	93.62308	47.43417	1.938	0.9819	1.69590	33		-5.260
30	34	24.47590	122.59222	52.82728	2.158	0.9301	8.57307	33		-5.587
25	34	24.47590	139.17102	57.21036	2.337	0.9609	5.44661	33		-5.395
20	34	24.47590	429.97899	102.05938	4.169	0.9506	4.41274	33		-11.009
POOLED							20.82854	165	0.12623	
WITHIN	170	122.37950	870.36517	304.95486			110.45468	169		
HETEROGENEITY							89.62614	4	22.40653	

(X = ∅)

(Y = %U)

Table 6. Percent of total flow in underflow, %U, for various values of ∅, underflow diameters and feed pressures. Overflow diameter, 0.50 inches. Feed diameter, 0.50 inches. Feed pressure, P_f, in pounds per square inch gauge.

	%U and feed pressures for underflow diameters, D_u, in inches											
∅	P_f	1/16	1/8	P_f	1/16	1/8	P_f	1/16	1/8	P_f	1/16	1/8
6.270	35	3.15	2.27	30	3.51	3.42	25	5.07	4.95	20	6.87	6.80
6.054	35	2.28	2.41	30	3.08	2.96	25	4.36	4.39	20	6.21	6.31
5.985	35	2.17	2.02	30	2.85	2.80	25	4.30	4.26	20	6.01	5.97
5.852	35	1.80	1.91	30	2.57	2.61	25	4.03	3.99	20	5.60	5.66
5.778	35	1.68	1.72	30	2.45	2.49	25	3.79	3.79	20	5.41	5.53
5.586	35	1.29	1.31	30	2.07	1.94	25	3.25	3.32	20	4.92	4.85
5.582	35	1.41	1.37	30	1.90	1.97	25	3.30	3.37	20	4.91	4.87
5.390	35	0.96	1.03	30	1.46	1.61	25	2.93	2.41	20	3.75	3.91
5.210	35	0.71	0.66	30	1.06	1.20	25	2.39	2.41	20	3.75	3.91
4.877	35	-	-	30	0.51	0.48	25	1.73	1.68	20	2.91	2.92
4.708	35	-	-	30	0.15	0.09	25	1.22	1.27	20	2.40	2.37
4.552	35	-	-	30	-	-	25	0.92	0.85	20	1.85	2.06

Table 7. Analysis of variance of table 6, volume split in the hydrocyclone for various values of ϕ, underflow diameters and feed pressures. Overflow diameter, 0.50 inches. Feed diameter, 0.50 inches.

SOURCE	d.f.	x^2	y^2	xy	b	R^2	d^2	d.f.	M.S.	a
35	17	1.81067	7.20625	3.49684	1.93121	0.9371	0.45301	16		-9.42040
30	21	4.80984	22.44384	10.37248	2.15651	0.9966	0.07546	20		-10.05335
25	23	6.71726	37.78260	15.91902	2.36986	0.9985	0.05663	22		-9.90134
20	23	6.71726	54.16490	19.06262	2.83785	0.9988	0.06792	22		-10.95420
POOLED							0.65302	80	0.00816	
WITHIN	84	20.05503	121.59759	48.85096			2.60419	83		
HETEROGENEITY							1.95117	3	0.65039	

$(X = \phi)$

$(Y = \%U)$

Table 8. Numerical values of ø for various values of overflow back pressure, P_o, in inches of water, underflow diameter, D_u, in inches, and overflow diameter, D_o, in inches.

P_o	D_o	ø at underflow diameters of 1/16	3.32	1/8
553.6	1/2	5.852	6.054	6.270
415.2	1/2	5.586	5.778	5.985
276.8	1/2	5.210	5.390	5.582
136.0	1/2	4.552	4.708	4.877
108.8	1/2	4.345	4.495	4.655
68.0	1/2	3.909	4.044	4.189
92.0	1/2	4.189	4.334	4.489
67.0	1/2	3.896	4.030	4.174
42.0	1/2	3.463	3.582	3.710
17.0	1/2	2.625	2.715	2.812
92.0	5/16	6.703	6.934	7.182
67.0	5/16	6.233	6.448	6.678
42.0	5/16	5.541	5.732	5.936
17.0	5/16	4.200	4.345	4.500

THE APPLICATION OF THE HYDROCYCLONE TO THE SEPARATION OF GLUTEN AND STARCH IN AQUEOUS SUSPENSION

by

STEWART H. MILLSTONE

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Several of the operations in the processing of cereal grains to obtain starch concern themselves primarily with the removal of gluten from the final starch product. It was proposed that the hydrocyclone, a relatively simple device occupying very little space, be used to effect the separation of gluten from starch as well as the removal of excess water from the slurry in which the particles are suspended. The following report contains a description of the investigation.

In this investigation, the percentage of gluten and the concentration of solids in the underflow stream was determined as a function of the feed and back pressures used, as well as the size of inlet and outlet conduits in the hydrocyclone. The gluten content was reduced from six per cent in the feed material to 0.6 per cent in the underflow, and the solids concentration was increased from two per cent in the feed material to as high as forty per cent in the underflow product through the use of the hydrocyclone. However, only a twenty per cent recovery of the total starch in the feed material was obtainable under the conditions necessary to reduce the gluten content to a satisfactory level.

The percentage of gluten and the concentration of solids in the underflow stream appeared to be mainly a function of the volume split in the hydrocyclone, i.e., the percentage of the total flow leaving at the underflow exit. Graphical representations of the gluten content and solids concentration as a function of the volume split can be found in the following report.

A prediction equation for the volume split as a function of pressures and inlet and outlet sizes was statistically determined as $\%U = k\phi + C$, where $\%U$ is the percentage of the total flow leaving at the underflow, and

ϕ is defined as $(\log P_o)/ D_o(1-D_u)$, where P_o is the back pressure applied to the overflow exit, D_o is the diameter of the overflow exit, and D_u is the diameter of the underflow exit. The proportionality constants k and C were found to be dependent on the size of feed inlet and the feed pressure used.

A prediction equation for the total volumetric flow through the hydrocyclone was also determined statistically as $GPM_t = k'\Delta P + C'$, where GPM_t is the total flow rate in gallons per minute through the hydrocyclone, ΔP is the feed to overflow pressure drop in pounds per square inch, and k' and C' are dependent on the feed and overflow sizes.

It was demonstrated that the hydrocyclone could be used to effect the separation of gluten and starch, and merits further investigation into the variables controlling the separation so as to increase the efficiency of operation.